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Division of Engineering and Applied Physics
Harvard University Cambridge, Massachusetts

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Harvard University

Cambridge, Massachusetts

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JOINT SERVICES ELECTRONICS PROGRAM

January 1, 1976 - December 31, 1976

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I. 1 Nonlinear Light Mixing Spectroscopy. Haim Lotem, R. T. Lynch, Jr., and N. Bloembergen, Contract N00014-75-C-0648; Research Unit 2.

The investigation of two-photon absorption (TPA) via three-wave mixing (3WM) experiments was extended: various organic solvents and their naphthalene solutions were explored. The results obtained[1,2] are quite accurate, with uncertainties much smaller than those of other TPA techniques. These results may be very useful in obtaining reliable TPA spectra, as references in other TPA experiments, and in determining TPA cross sections when the classical techniques are troublesome, particularly when UV laser frequencies are used.

The first observation of destructive interference between imaginary contributions to the third order susceptibility $\chi^{(3)}$ was made.[3] The

destructive interference was observed both in the 3WM experiment and in the Raman-induced Kerr effect (RIKE) experiment. Perturbation theory predicts a change in the sign of the imaginary part of the Raman contribution to $\chi^{(3)}$ when $\omega_1 - \omega_2$ changes sign, while no change occurs in the imaginary part of the TPA contribution. Therefore, by performing the experiment with $\omega_1 - \omega_2$ first positive, then negative, in a system with a large TPA effect, we could observe the addition and subtraction of the imaginary parts of the Raman and TPA contributions to $\chi^{(3)}$. This destructive and constructive interference is very useful in the calibration of TPA cross sections vs. Raman cross sections in the 3WM experiment since it improves the accuracy of the measurement both in systems with very large TPA where the minimum in the 3WM trace due to interference of real contributions to $\chi^{(3)}$ is filled in, and in systems with small TPA where scattered light in the minimum region is a severe problem. In addition, the destructive interference may be used for enhancing the sensitivity of the four-wave mixing experiment by canceling the troublesome imaginary electronic background which cannot be eliminated by the method described in Ref. 4.

The complete tensor $\chi^{(3)}$ of the non-cubic crystals quartz and calcite was determined in a 3WM experiment. Using group theory arguments and Kleinman symmetry, which is a good approximation in these large gap crystals, the number of independent tensor elements of $\chi^{(3)}$ is reduced from 81 to 4. By taking 3WM traces near strong Raman modes of the crystals with different crystal orientations and different electric field polarizations we obtained the background tensor elements which appear in Table I. These results depend, of course, on the magnitude of the

Raman cross section. The spontaneous Raman cross sections quoted in the literature disagree, and so we measured these cross sections in a spontaneous Raman apparatus relative to the standard 991 cm^{-1} mode of benzene. These cross sections are also listed in Table I.

Table I

	Quartz	Calcite
$\chi^{(3)}_{xxxx}$ [10^{-15} esu]	7	6.3
$\chi^{(3)}_{zzzz}$ [10^{-15} esu]	7	4.3
$\chi^{(3)}_{xxzz}$ [10^{-15} esu]	2.3	2.5
$\chi^{(3)}_{yyyz}$ [10^{-15} esu]	0.1	0.7
$\frac{d\sigma}{d\Omega}$ $\frac{10^{-30}\ cm^2}{\text{unit cell} \cdot sr}$	3	7

The three wave light mixing experiments in CuCl, showing the interference of two photon absorption of the Z_3 exciton resonance and the infrared Raman polariton resonance have been completed and published in final form.[5]

Invited papers on the subject matter, were presented at the International Conference on Quantum Electronics, held in Amsterdam, June 1976, and at the annual meeting of Optical Society of America, Tuscon, October 1976.

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I. 2 Two-Photon Absorption in Solids with Ruby Pumped Dye Lasers.

H. Lotem, Cid B. deAraujo and N. Bloembergen, Contract N00014-75-C-0648, Research Unit 2.

We have performed direct, absolute and relative measurements of the two-photon absorption (TPA) coefficient in several crystals. We have made these measurements utilizing a strong Ruby laser which induced absorption at the frequency of a narrow-band dye laser probe beam at $\lambda = 5800$ Å. The measurements were performed in order to show the possibility for the direct and reliable calibration of TPA coefficients vs. well-known cross sections of the inverse Raman effect.[1]

Some preliminary results of TPA cross sections normalized to the Raman cross section of the 2855 cm^{-1} mode of cyclohexane are:

CdS: $.056 \pm .004$ cm/MW

T_iO_2: $.023 \pm .005$ cm/MW

SrT_iO_3: $.003 \pm .001$ cm/MW

We note that the uncertainty in our measurements is much smaller than the uncertainty of the conventional TPA measurements which are critically dependent on the characteristics of the laser beam used. Our measurement is almost independent of the temporal and spatial properties of the beams and practically any kind of strong laser may be utilized in the experiment. This is especially important in the blue and uv portion of the spectrum where the conventional TPA techniques are troublesome. The dyes may be pumped by the second harmonic of the ruby laser. Extension of this method to the uv spectral region is in progress.

Reference

1. Haim Lotem, J. H. Bechtel, and W. L. Smith, Appl. Phys. Lett. 28, 389, 1976.

I. 3. Optical Damage by Picosecond Light Pulses. W. L. Smith, J. H. Bechtel and N. Bloembergen, Contracts N00014-75-C-0648, ARPA Grant F44620-75-C-0088 and NASA Grant NGL 22-007-117; Research Unit 3.

A comprehensive Technical Report No. 665 on Dielectric Breakdown Induced by Picosecond Laser Pulses was distributed in October 1976. The microscopic morphology of the damage sites has been published in a scientific journal.[1] The extension of the damage studies to the green (0.53 μm) and the near ultraviolet (0.34 μm) has also been accepted for publication.[2]

It appears that in the farther ultraviolet damage thresholds may be determined by three- or two-photon absorption rather than by avalanche ionization. This is indicated by the attainment of the maximum of the damage threshold as a function of decreasing wavelength.

Mr. W. L. Smith obtained the Ph. D. degree and is now working on laser research at the Lawrence Livermore Laboratory. Dr. J. H. Bechtel has left the project and his present address is the General Motors Research Laboratory in Warren (Mich.).

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1. W. L. Smith, J. H. Bechtel and N. Bloembergen, Optics Comm. 18, 592, 1976.

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I. 4. Two Photon Absorption and Superbroadening with Picosecond Pulses.

J. H. Bechtel, P. L. Lin, W. L. Smith and N. Bloembergen,

Contracts N00014-75-C-0648, ARPA Grant F44620-75-C-0088 and NASA Grant NGL 22-007-117; Research Unit 3.

Superbroadening by picosecond pulses in water (H_2O and D_2O) has been investigated with picosecond pulses at 1.06 μm and 0.53 μm. Continuum "white light" picosecond pulses have been produced with the Nd-Yag laser system and a quantitative determination of the threshold for this process has been made. It has been determined that the threshold for superbroadening is always preceded by the lower power threshold for

catastrophic self-focusing and/or the intensity threshold for dielectric avalanche breakdown. A manuscript, giving a detailed discussion of experimental findings by others and a comparison with the theory of index variation due to plasma formation, has been submitted for publication in Physical Review A.

A quantitative study has been made of photo-electric emission from tungsten, molybdenum and tantalum surfaces, following two-photon absorption from 0.53 μm wavelength picosecond pulses. A paper has been accepted for publication in the Physical Review. This work will be continued with a quantitative investigation of the dependence on polarization, angle of incidence and wavelength of multi-photon photo-electric emission.

Two photon absorption studies of transparent ultraviolet laser window materials have been initiated. Preliminary results for two-photon absorption cross sections at 0.26 μm wavelength have been obtained in several alkalihalides, quartz and KDP. Data will also be taken at 0.34 μm wavelength. The picosecond pulse facility is at present devoted to the continuation of this work.

I.5. Ultra-High Resolution Two-Photon Spectroscopy in Atomic Vapors.
M. M. Salour and N. Bloembergen, Contract N00014-75-C-0648; Research Unit 2.

During this reporting period we have employed a powerful, narrow band pulsed dye laser oscillator-amplifier system to investigate:

1. Fine structure splittings of a series of excited 2_D states in sodium, excited 3^2D, 5^2D, 6^2D, 7^2D and 8^2D fine structure interval

were for the first time measured using Dopper free two-photon spectroscopy technique. These measurements, that had never been performed in the past, have revealed many interesting features about the inversion of these levels. We have made a systematic study of their properties.[1]

2. The interpretation of atomic isotopic shifts relies partly on the knowledge of nuclear structure. Conversely, it can provide some important information on the structure of nuclei. We have measured the isotopic shifts in three levels of the $2P^5 7d$ states of neon. The pressure-tuned pulsed dye laser was synchronized with the chopped RF discharge in order to excite the atoms with two-photon from the metastable $2P^5 3S$ state to the excited $2P^5 7d$ state. We have also studied the collisional broadening and shifts of these three levels and a systematic study of the collision process in two-photon excitation is studied. A detailed paper on this subject is currently being written.[2]

3. We have made some preliminary measurements on the isotopic shift in highly excited $11\,^3P_0$ level of mercury; combing techniques of optical double resonances and Doppler-free two-photon spectroscopy. This technique is applied for the first time for investigation of the properties of the atoms in the highly excited Rydberg states, where the isotopic displacement is purely due to the mass shift term in the effective Hamiltonian and no volume shift comes into play.[3]

4. We have for the first time utilized a highly stabilized pressure-tuned cw dye laser oscillator with three stages of pulsed amplifier to generate highly intense, monochromatic and Fourier limited pulses.[4] Using the output of this laser we have generated two coherent, phase-locked,

time-delayed short pulses originating from the same initial pulse. We have demonstrated[5] that in the same way that the diffraction pattern through two spatially separated slits exhibit interference fringes within the diffraction profile corresponding to a single slit, using these two-time-delayed "phase-locked" pulses, one obtains in the profile of the Doppler-free two-photon resonances, interference fringes with a splitting proportional to T^{-1} (T = delay between the two coherent pulses) much smaller than the spectral width τ^{-1} (τ = duration of each pulse). Furthermore, we have eliminated the diffraction background and isolated these fringes by inducing a 90^{o} phase shift (i.e., 180^{o} for two-photon) between every other pair of coherent pulses and by subtracting the resulting fluorescence from pairs of coherent pulses with and without the phase shift. This technique has already demonstrated to be extremely promising for situations where the contrast of the fringes is poor. For example, where T is chosen longer than the radiative lifetime in order to get a fringe splitting smaller than the natural line width. A brief experimental and theoretical description of this novel high-resolution spectroscopic technique has been submitted to Physical Review Letters.

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6. M. M. Salour, "Isolated Ramsey Fringes in the 3^2S-4^2D two photon transitions," to be published.

7. M. M. Salour, "High resolution two-photon spectroscopy in atomic vapors," Proceedings of the 5th International Conference on Atomic Physics, Berkeley, Calif., July, 1976.

I. 6 Nonlinear Conical Refraction. Anita J. Schell and N. Bloembergen, Contract N00014-75-C-0648; Research Unit 2.

The experimental investigation of nonlinear conical refraction in a single crystal of α-iodic acid has been continued. It was found that accidentally the optic axes at 1.06 μm and 0.53 μm nearly coincide. Therefore a dye laser, pumped by a ruby laser, was used to provide a fundamental wavelength near 0.84 μm. The second harmonic at 0.42 μm is just below the uv absorption edge of the crystal. The optic axes at these two wavelengths are well separated by 1.8^{o} degrees.

When the fundamental light is incident parallel to the fundamental optic axes at 0.84 μm, a forced second harmonic cone is observed at 0.42 μm, in addition to a free second harmonic ray. When the fundamental light is incident parallel to the second harmonic optic axis, a free cone at 0.42 μm is observed, in addition to a forced ray. The observed patterns are a very sensitive function of crystal orientation in the vicinity of the directions of the optic axes. The experimental work has now been completed.

A short communication has been accepted for publication. A post-deadline paper was presented at the International Conference on Quantum Electronics in Amsterdam, June 1976.

Further theoretical computations on conical refraction in piezoelectric biaxial crystals, which always display natural optical activity, are currently underway. These will be compared with the detailed intensity and polarization patterns, obtained at both the fundamental and second harmonic frequencies.

Reference

1. A. J. Schell and N. Bloembergen, Optics Comm., to be published, 1977.

I. 7. Picosecond Nonlinear Optics at 10.6 μ. H. S. Kwok and E. Yablonovitch, *Contract* N00014-75-C-0648 and ARPA Grant F44620-75-C-0088; Research Unit 4.

Further progress has been made on the development of the picosecond CO_2 laser system. During the past year, a systematic study of the pulsewidth formed as a function of the system parameter was carried out. Because it was impossible to have picosecond resolution by direct observation at 10.6 μ an autocorrelation method was employed.[1] It was found that a linear theory for the formation of the free optical induction decay pulse was sufficient to predict the pulsewidth behavior, namely, the pulse rises rapidly to its peak in 10 psec, and then decays with a time constant T_2/N where T_2 is the dipole relaxation time of the CO_2 molecules

and N is the logarithmic absorption depth in nepers. By measuring the ultimate speed of the plasma shutter, we are able to infer that the ionization front of the breakdown propagates with a velocity of 10^8 cm/sec. It is now an established fact that 30 psec pulses of about 0.5 MW peak power and little fluctuation can be generated by our prototype system.

Moreover, in order to make the laser system simpler to operate, we have introduced a modification of the old triggering method for the breakdown plasma.[2] It bases on the replacement of the d.c. spark by a metal block, and the triggering electrons then come from the surface microplasma instead of the d.c. breakdown spark.[3]

The picosecond CO_2 pulses are now being applied to study the behavior of solid state plasma at high laser intensities. We could use laser intensities of up to 3×10^9 W/cm^2 *without damaging the crystal* because we are using pulses. It is expected that the band structure will be severely altered[4] and large nonlinearities could be observed. To date, we have measured the two-photon absorption coefficient of InSb at such high intensities, and it was found that it is the same as the lower intensity value.[5] This could imply a very large electron-hole pair generation rate. The plasma may become critical within the duration of the picosecond pulse. We plan to continue the study of the interaction of this electron-hole plasma with the high intensity laser field.

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I. 8. Laser-Plasma Interaction Studies. Paul Kolodner, Jerry Black and Eli Yablonovitch, Contract N00014-75-C-0648 and ARPA Grant F44620-75-C-0088; Research Unit 4.

In the last year, our understanding of the mechanisms by which intense laser light interacts with plasmas has improved substantially. A year ago, we reported the first observation of x-rays emitted from plasmas produced by optical breakdown of ultraclean, ultrapure gas. These emissions occurred, in H_2 gas, at pressures exceeding 150 torr. Our interpretation is as follows: most theories of laser-plasma interaction predict substantial interaction only in that region where the plasma frequency, ω_p, equals the laser frequency ω. This occurs in the layer where the plasma density n equals the so-called "critical density," n_{cr}, which for our CO_2 laser ($\lambda = 10.6\ \mu m$), has the value $10^{19}\ cm^{-3}$. In neutral H_2 gas at 150 torr, the density of H_2 molecules is exactly $1/2\ n_{cr}$. Thus our result indicates the the laser doubly ionizes the H_2 gas without any compression of the resulting plasma, so that a critical density exists for pressures in excess of 150 torr. This enables the interaction which produces the x-rays we observe.

We have since carried out similar investigations with other gases, using emitted x-rays and electrons as diagnostics. In some gases (N_2, He, Ne, CH_4), the process of ionization is similar, although the

ultimate ionization state is higher in N_2, Ne, and CH_4 than in H_2 and He, leading to emission at correspondingly reduced pressures. In the heavy inert gases, however (Ar, Kr, Xe), the turn-on pressures are too low to produce a critical density at achievable ionization states. To explain this result, we hypothesize that the ionization of the gas is produced by the so-called "laser-driven shock wave," which compresses the resulting plasma, producing a critical density at lower pressures than expected. A forthcoming paper will describe these experiments, which are taking place within the larger framework of our investigation of ionization phenomena in gases[2] and the physics of gaseous laser targets for fusion.

In conjunction with this work, we have made the first experimental verification of the theory of resonant absorption of laser light by plasmas.[3] In this theory, the laser light interaction with the plasma takes place by resonant coupling to plasma oscillations in the "critical layer," where $n = n_{cr}$. As a result of this coupling, we see electrons emitted from the plasma in a direction not predicted by any other theory of laser-plasma interaction. We use this phenomenon both as diagnostic for ionization mechanisms, as above, and to measure the plasma density gradient scale length, which is about one micron. This direct observation of the resonant absorption effect was first made in gaseous targets. We have also made the first observation of this effect in a solid target, in this case a beryllium sheet. In solids, presumably because of the turbulence of the cirtical layer, the effect is much weaker than in gases; this will be subject of another forthcoming paper.

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II. SOLID STATE ELECTRONICS

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II. 1 Raman Scattering in Nematic and Smectic Liquid Crystals. Shen Jen, Noel A. Clark, S. Asher, and P. S. Pershan, Contracts NSF-DMR76-22452 and NSF-DMR76-01111; Research Unit 5.

Polarized Raman studies of orientational statistics on thermotropic liquid crystals that were mentioned in previous reports are now completed. A manuscript on this subject is scheduled for publication in the May 1 issue of the J. Chem. Phys. We are now attempting to carry out a similar set of studies on lyotropic liquid crystals. The primary materials of

interest here will be lipid compounds that are relevant to biological membranes. The primary difficulty in this experiment will be to achieve sufficient signal to noise. At the present time we expect signal to noise will be limited by the small size of the aligned samples that can be prepared.

II. 2 Brillouin Scattering from Liquid Crystals. M. Fisch, Jean Pierre LePesant, Noel A. Clark, and P. S. Pershan, Contracts NSF-DMR76-22452 and NSF-DMR76-01111; Research Unit 5.

The principal accomplishments of this project to date have been described in earlier annual reports. At the close of last year Jean Pierre LePesant completed his experiments on Brillouin studies of pure dipalmitoyl phosphatidylcholine at varying water concentrations and temperatures and also measurements of this same lipid containing 33 mole % cholesterol. We are now in the process of completing the analysis of that data. However, certain conclusions are already in evidence.

1. Above approximately 15% water and at temperatures in excess of approximately 40°C, the pure dipalmitoyl phosphatidylcholine samples are essentially elastically isotropic. The elasticity gets stiffer as the temperature is lowered. However, within this concentration range, the measurable elasticity is independent of water concentration. At low water concentration, the samples are considerably stiffer.

2. Below approximately 40°C the elastic properties become still stiffer; they become sensitive to the amount of water contained and

furthermore there is some anomalous temperature dependence that can be related to the microscopic properties of lipid molecules in these bilayers.

3. The effect of cholesterol on these samples is to stiffen the elasticity of the bilayer considerably at temperatures above 40°C. Below 40°C there are small, subtle, but significant alterations in the elastic properties of these samples.

This work will continue by first extending the measurements to intermediate water concentrations where anomalous temperature dependent changes were observed. At the present time we do not have enough data in this region to know exactly what is happening and when. There is a possibility that one might observe a macroscopic manifestation of a phase transition in which the elasticity of the lipid bilayers makes a sudden qualitative change. In addition to this we hope to extend these measurements to other lipids and to systems containing other membrane associated ingredients.

The principal long-range objective of this project is to understand the macroscopic elasticity of these multilamella lipid samples and then to relate these properties to the observable elastic phenomena in biological membranes.

II. 3 Optically Induced Effects in Liquid Crystals Using Interdigital Electrodes. D. Luippold and P. S. Pershan, Contracts NSF-DMR76-22452 and NSF-DMR76-01111; Research Unit 5.

Earlier studies on the flexoelectric coupling between liquid crystals and a periodically applied electric field are currently being extended to high

frequencies. Linear coupling between the field produced by interdigital electrodes and the macroscopic properties of the liquid crystal itself induce Bragg diffraction at angles that would not be present in the absence of a linear effect. All work that we have done up until now was confined to frequencies below approximately 100 kHz. However, the system we are currently constructing should extend our capability to approximately 30 MHz. The principal new ingredient is a balance phase sensitive, RF frequency demodulator.

II.4 Physical Studies of Lipid Smectic Systems. L. Powers, S. Asher, and P. S. Pershan, Contracts NSF-DMR76-22452 and NSF-DMR76-01111; Research Unit 5.

The accomplishment in this project area described in previous years is such that many of the other project areas described herein have begun work on lipid samples. This project, as a separate entity, will thereby terminate with the publication of a manuscript that is now in preparation. Further progress related to this project will be described under separate project areas.

II. 5 Forced Thermal Diffusivity Studies. Winston Chan, Noel A. Clark, and P. S. Pershan, Contracts NSF-DMR 76-22452 and NSF-DMR 76-01111; Research Unit 5.

The new technique of "forced thermal diffusivity" was described in previous progress reports.

During the last period we have succeeded in obtaining both thermal diffusivity and water diffusion measurements in multilamella lipid samples using this technique. The principal new technological achievement here has been the development of an optical heterodyne technique by which large background signals can be subtracted away from the smaller signals of interest. One principal result obtained to date has been in samples of pure dipalmitoyl phosphatidylcholine containing approximately 20% water. The diffusion constant for water has been measured as a function of temperature. The most significant single result is that the activation energy for diffusion is approximately 2. 5 to 3 times larger than the activation energy for the viscosity of bulk water. This suggests that even in samples containing relatively large amounts of water, where the water was thought to be relatively free, it is considerably less free than in bulk water. We hope to continue these studies in the next period in order to understand how this diffusion process varies with water content and also with different lipids.

II.6 Ferroelectric Liquid Crystals. Robert B. Meyer, Stephen Garoff, Ronald Pindak, Noel A. Clark, Charles Young, Contracts NSF-DMR76-22452 and NSF-DMR76-01111; Research Unit 5.

Several studies of electro-optical properties of these materials have been made. The electro-optical response due to a piezoelectric effect in the smectic A phase above the smectic A - smectic C phase change has been studied as a function of temperature near the phase change, to examine critical phenomena associated with this transition. We have determined the critical exponent $\gamma = 1.11 \pm 0.06$.

In freely suspended thin films of these materials, the structure, energetics, and dynamics of electric field induced domain walls have been studied. The wall structure is well described by the simplest theory, and some special effects due to the gradients of the polarization field and the coupling of polarization to curvature in these walls have not been found to be important. From the structure and dynamics, then, one can determine ratios of the mean curvature elastic constant to polarization density and rotational viscosity.

In these same films, we have begun to measure the spectrum and intensity of light scattered by fluctuations of molecular orientation, which are coupled to fluctuations of the polarization orientation. We can again measure the ratio of elastic to viscous coefficients, and, in the case that fluctuations produce polarization space change, we can measure the electrostatic contribution to the free energy of the fluctuations. These measurements are in agreement with those on the domain walls.

II.7 Mechanical Properties of Smectic Liquid Crystals. Charles Rosenblatt, Ronald Pindak, Noel Clark, and Robert B. Meyer, Contracts NSF-DMR76-22452 and NSF-DMR76-01111; Research Unit 5.

In our studies of the relaxation of uniaxial stress in smectic A liquid crystals, we have found a new kind of defect structure, which plays a dominant role. It is a confocal pair of parabolic line defects, which is associated with an undulation and cusp-like deformation of the smectic layers. We have calculated the structure of the smectic layer in the vicinity of these defects, the interactions between defects, and the interactions with sample boundaries, the latter interactions being viewed in simple limiting cases. The agreement of the observations with our model of the defects is excellent, and more detailed analysis is underway.

II.8 Properties of Liquid Crystal Free Films. Charles Young, Charles Rosenblatt, Ronald Pindak, Noel A. Clark, Robert B. Meyer, and Peter S. Pershan, Contracts NSF-DMR76-22452 and NSF-DMR76-01111; Research Unit 5.

Some of the important results are summarized under the section describing Ferroelectric Liquid Crystals. In general, polarization reflection microscopy, light scattering, and ellipsometry are the techniques we are using. In addition to the studies summarized elsewhere, we are studying phase changes in the two dimensional limit. In the thin films, the phase diagram observed in the bulk is drastically modified, and we have begun systematic studies of the phase diagram as a function of film thickness.

Also, in two dimensions the nature of the ordering at a phase change is believed to be different from that in three dimensions, and we have begun experiments to detect these differences, at both the smectic A - smectic C and smectic C - smectic H phase changes.

II. 9 Far-Infrared Frequency Dependence of the Josephson Effect in Point Contacts. D. A. Weitz, W. J. Skocpol, and M. Tinkham, Contracts N00014-75-C-0648, N00014-76-C-0032 and NSF Grant DMR76-11323; Research Unit 1.

Laser radiation at frequencies of 604 GHz (496 μm), 1.48 THz (202 μm), 1.76 THz (171 μm), and 2.52 THz (119 μm) from an optically pumped FIR molecular laser has been focussed on Nb-wire superconducting point contacts, and the magnitude of the ac Josephson effect steps induced at voltages $N\hbar\omega/2e$ has been systematically studied. For high-resistance, well-coupled junctions the power dependence of the induced steps is surprisingly reproducible. Although qualitatively similar to the Bessel function behavior expected from a voltage-biased, frequency-independent model, the power dependence of the data can be better fit using a frequency-dependent (Werthamer) model which takes into account the peak and rolloff of the Josephson response at and above the frequency corresponding to the superconducting energy gap ($\sim$ 1.3 THz). Compared to the dc critical current, the magnitude of the induced steps is smaller than expected from either model, varying systematically by factors of 2 to 9 with fundamental frequency and step number.

This reduction is larger than can be accounted for by the combination of noise rounding and the intrinsic frequency dependence of the Josephson effect predicted by the Werthamer theory. Independent evidence indicates that heating effects are negligible in these high-resistance contacts. Other possible explanations of this reduction are being investigated.

II. 10 Extended Frequency Range for Josephson Effects in "Variable Thickness" Microbridges. M. Octavio, W. J. Skocpol, and M. Tinkham, Contracts N00014-75-C-0648 and N00014-76-C-0032; Research Unit 1.

We have extended the operating range of microbridge Josephson devices to far infrared frequencies by minimizing the temperature rise due to Joule heating in the vicinity of the bridge.[1] By cutting tin or lead films so as to leave a thin bridge connecting thick banks, we have achieved a well-cooled three-dimensional geometry which gives greatly improved performance. Conventional bridges have been limited to approximately 0.5 mV (250 GHz) whereas our improved bridges have shown Josephson steps as high as 3.7 mV (1.8 THz) corresponding to the 187th harmonic of X-band microwaves. This frequency corresponds to a wavelength of 170 μm, well into the far infrared. We have confirmed experimentally that such bridges are better cooled by using the position of the energy gap structure on the I-V curve as a local thermometer.[2] Smaller temperature rises correlate with thicker banks, thinner bridges, and better performance.

Our recent detailed theoretical analysis of the heating effects in this three-dimensional geometry[3] supplements our previous analysis which drew attention to the superiority of three-dimensional over one- and two-dimensional geometries.[1] One of the surprisingly general results which comes out of the analysis is that the critical current (and hence the magnitude of the Josephson oscillations) cuts off as e^{-P/P_0} where P is the total power dissipated and P_0 is a constant of order 10 μW for a number of materials (from aluminum to niobium), and is insensitive to the details of the three-dimensional geometry. This result agrees well with the decrease in amplitudes of the Josephson steps observed with increasing bias voltage in our variable thickness bridges, and with the much higher cutoff voltage observed in higher-impedance point contacts.

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II. 11 Laser-Induced Disequilibrium in Superconducting Films. L. N. Smith, A. D. Smith, and M. Tinkham, Contracts N00014-75-C-0648, N00014-76-C-0032, and NSF Grant DMR76-11323; Research Unit 1.

Several experiments, with a variety of superconducting materials, give indirect evidence that the nonequilibrium state created in a film by

optical illumination is inhomogeneous over a range of intensities so that it splits up into a mixture of normal and superconducting regions. Some previous attempts have been made to understand this state theoretically, but they rely on oversimplified models of the nonequilibrium excitations, and provide little insight into the nature of the inhomogeneous state. These theories have been hampered by a lack of direct experimental measurements of this state, and the extreme difficulty of calculating the distribution of the nonequilibrium excitations.

We have observed this inhomogeneous state by monitoring the I-V characteristics of a long, narrow tin bridge illuminated with pulses produced by our optical scanning system in conjunction with our cw Ar-ion laser. The preliminary data support the idea that the length scale which characterizes this state is the quasiparticle diffusion length Λ. We have developed a theory[1] of this state whose central feature is a diffusion-driven spatial instability related to the general shape of the nonequilibrium quasiparticle distribution function. After improving the uniformity of the illumination of the bridge, we should be in a good position to test some of the other predictions of this theory.

Tunnel junctions are an excellent probe of the state of a superconducting film, because they are sensitive to the shape of the quasiparticle distribution, provide a direct measurement of the energy gap, and can in principle be made arbitrarily small. While the basic theory relating the quasiparticle distribution to the I-V characteristics is well-known, experimental I-V curves usually contain additional features which are not well understood and which complicate the extraction of the quasiparticle distribution from the data. We have made some progress in

understanding how to do this, and have successfully applied our techniques to data from a previous experiment with aluminum junctions.[2] We intend to use these techniques to study the disequilibrium produced in tin tunnel junctions by our FIR lasers, which create excitations localized at energies near the gap, where the dynamics which are responsible for the distribution are the best understood theoretically. We also hope to use this technique to study the disequilibrium created by our Ar-ion laser.

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1. L. N. Smith, "Diffusive Instability in Optically Excited Superconductors," contributed paper, March APS meeting, 1977.

2. L. N. Smith, Ph. D. Thesis, U. of Illinois, 1975.

II. 12 Production and Structural Measurements on Sputtered Amorphous Group 4 and Group 3-5 Compounds. G. A. N. Connell, T. D. Moustakas and W. Paul, Contracts N00014-75-C-0468, NSF DMR75-18477, NSF DMR76-15325, NSF DMR72-03020 and NSF DMR76-01111; Research Unit 6.

The deposition of amorphous films of group 4 (Ge,Si) and selected group 3-5 semiconductors by rf sputtering in argon, with deposition rate and substrate temperature as variable parameters, is now under good control. The normal structural measurements (X-ray, thickness, density, electron microprobe) are also carried out routinely.

II. 13 Production of Amorphous Ge and Si, Amorphous Hydrogenated Ge and Si, and Doped (B, N, P) Amorphous Ge and Si. D. A. Anderson, G. A. N. Connell, A. J. Lewis, T. D. Moustakas, J. R. Pawlik and W. Paul, Contracts N00014-75-C-0468, NSF DMR75-18477, NSF DMR76-15325, NSF DMR72-03020 and NSF DMR76-01111; Research Unit 6.

Our earlier work on the sputtering of amorphous Ge, with hydrogen incorporated to compensate dangling bonds, has been extended in several ways:

(a) Amorphous $Si_{1-x}H_x$ has been rf sputtered at four substrate temperatures between room temperature and 450°C and as a function of hydrogen partial pressure in the sputtering gas. The atomic percent x ranges from 0 to approximately 12. It is straightforward to substitute D for H.

(b) Both amorphous $Si_{1-x}H_x$ and amorphous $Ge_{1-x}H_x$ have been successfully doped n-type and p-type by sputtering at several substrate temperatures with partial pressures of N_2, PH_3 or B_2H_6 in the Ar-H sputtering gas. As is normal, a variety of conducting and insulating substrates have been used, some of them with pre-deposited electrodes of different materials. In addition, p-n junctions have been made by tandem doping by P and B.

All of the films under (a) and (b) have been produced either a fraction of a micron thick, for optical and transport measurements, or in thickness up to 20 microns when spin resonance or vibrational infrared absorption were to be studied.

II. 14 Study of Doping, Schottky Barrier and p-n Junction Formation in Amorphous Ge and Si. W. Paul, A. J. Lewis, G. A. N. Connell and T. D. Moustakas, Contracts N00014-75-C-0468, NSF DMR75-18477, NSF DMR76-15325, NSF DMR72-03020 and NSF DMR76-01111; Research Unit 6.

Addition of a partial pressure of H to the Ar used in rf sputtering of Ge and Si leads to a very large decrease in conductivity attributable to a drastic reduction in the pseudogap state density. The additional inclusion of a partial pressure of B_2H_6 gives an increase in conductivity and a large (1 mV/K) positive thermoelectric power; it is inferred that B is doping the material with acceptors. Alternatively, the inclusion of a partial pressure of PH_3 also increases the conductivity by orders of magnitude and gives a similarly large negative thermoelectric power; it is inferred that P produces donor centers. Sputtering onto pre-deposited selected metal electrodes, or sputtering followed by deposition of selected metal electrodes produces very good rectification characteristics. High work function metals on (n)-a-Si and low work function metals on (p)-a-Si give good Schottky barriers. When tandem doping by P and B is carried out, and suitable "ohmic" metal contacts are used, good rectification characteristics ascribable to p-n junctions are found. These results demonstrate conclusively for the first time that these amorphous semiconductors may be doped in controlled fashion by rf sputtering. The mechanism of recitification poses a theoretical challenge (it is not at all clear that the usual theory is adequate) and the impressive rectification characteristics may have potential for devices.

The optical properties of the doped a-Ge and a-Si have also been studied. While H-compensation of dangling bonds shifts the absorption edge to higher energies, the addition of both B and P produces shifts to lower energies. This is consistent with the introduction of either acceptor states (B) above the valence band maximum or donor states (P) below the conduction band minimum energy. The photoconductivity spectra edges show similar shifts. The magnitude of these edge shifts by doping is large: up to 0.5 eV has been measured.

The magnitude of the photoresponse is affected, not only by substrate temperature and partial pressure of H, but also by inclusion of P or B. However, while P-doping has been found to increase the photoconductivity by a factor of 10, B-doping decreased it by 10^3. In addition, the decay time of the photoconductivity after a pulse of radiation increases by a factor of about 5 for the P-doped a-Si, while such decays are not measurable for the B-doped material. It is proposed that such differences may have to do with the relative probabilities of carrier recombination with multiphonon emission, which are greater for the B, which has high energy B-Si vibrational modes, than for the heavier mass P.

II. 15 Study of Conditions for the Maximum Reduction of Pseudogap States in Amorphous Silicon. D. A. Anderson, Eva Black, T. D. Moustakas, J. R. Pawlik and W. Paul, Contracts N00014-75-C-0468, NSF DMR75-18477, NSF DMR76-15325, NSF DMR72-03020 and NSF DMR76-01111; Research Unit 6.

Both from the point of view of basic research and of device optimization, it would be useful to establish the conditions for maximum reduction of the gap states in a-Si. Indeed, this has been one of the thrusts of all past work involving annealing, substrate temperature variation, rate of deposition change, and hydrogen incorporation. From the device viewpoint, this condition clearly permits the most efficient n- and p-type doping with "hydrogenic" donors and acceptors to proceed. In our work on devices, it has been the compensation of dangling bonds by addition of H to the sputtering gas which has permitted doping and junction formation.

A matrix of a-$Si_{1-x}H_x$ samples produced, as described under item 2, as a function of x and substrate temperature has been subjected to the following measurements:

(a) conductivity vs. T over a sufficiently wide range of T that activation energies for conduction may be derived from plots of ln σ vs. 1/T;

(b) thermoelectric power vs. T on a selection from the samples, to determine whether the activation energies for conduction and carrier generation are different, as we have found in earlier investigations;

(c) absorption edge vs. photon energy, to give information about changes in the density of states;

(d) photoconductivity vs. photon energy, to be compared with (c) to give information about quantum efficiencies.

The analysis of the results of this investigation is not complete, but the following conclusions may already be drawn.

(a) An expected monotonic shift, as a function both of substrate temperature and partial pressure of H in the sputtering gas, of absorption edge vs. photon energy (to larger apparent pseudogap), of photoconductivity edge vs. photon energy, of activation energy for conduction, of magnitude of dark conductivity at low temperatures, and of magnitude of the photoconductivity per absorbed photon at a fixed T, is not found. Instead, there seem to be extrema in some of these quantities for a narrow range of substrate temperature and partial pressure of H.

(b) One possible explanation of the above result is a dependence of H incorporation, x, not only on the partial pressure of H in the sputtering gas, but also on substrate temperature--specifically, a decrease in x as T_s is raised. Attempts are in progress, therefore, to determine x accurately from the magnitude of the infrared absorption caused by local Si-H vibrational modes. We intend also to explore the possibility of observing Raman scattering from such localized modes, and of measuring the amount of evolved H as samples are heated.

(c) A different type of explanation, which will gain currency if x is linearly related to H partial pressure, is the possibility that H introduces new electronic states in the pseudogap or in the Si conduction band, and that the effects of these compete with the effect of removal of dangling bond states from the pseudogap by H-compensation.

II. 16 Photoconductivity in the Amorphous $Ge_{1-x}H_x$ System. T. D. Moustakas, G. A. N. Connell and W. Paul, Contracts N00014-75-C-0468, NSF DMR75-18477, NSF DMR76-15325, NSF DMR72-03020 and NSF DMR76-01111; Research Unit 6.

These measurements have been extended in the following ways:

(a) a series of films with $x = 0$, 4.1, 7.4, and 12.9 and of thickness about 1 μ have been produced at a deposition temperature of 25°C. Films of this thinness display essentially no bolometric effect compared with the photoconductive one.

(b) the conductivity and steady state photoconductivity under illumination by He-Ne and GaAs lasers and the monochromatised radiation from a quartz iodine tungsten lamp have been measured for all films between $T = 77$ K and $T = 300$ K.

(c) the dependence of the photoconductivity on illumination intensity has been measured on all films at 77 K and 300 K for illumination by a He-Ne laser.

(d) the spectral dependence of the photoconductivity has been measured on all films at 77 K between $h\nu = 0.5$ eV and $h\nu = 2.2$ eV.

(e) the rise and decay rates of the photoconductivity for all films under illumination by a pulse from a GaAs laser have been measured at temperatures between 77 K and 300 K.

An extensive analysis of these results has been completed and has led to the following conclusions:

(a) addition of H displaces the photoconductivity edge to higher energies, consistent with previously observed displacements of the

absorption edge of similarly hydrogenated Ge films. The most likely explanation of this is removal of pseudogap states as a result of compensation of Ge dangling bonds by the H.

(b) the steady state photoconductivity vs. T and the pulsed photoconductivity decay rate vs. T can be combined to give the drift mobility of the electrons vs. T. This yields a drift mobility with an activation energy of 0.1 eV at high temperatures which decreases to a very low value ($\sim$ 0.01 eV) at temperatures below about 200 K. While several explanations of this behavior are conceivable, the preferred model is that of polaron hopping at high temperatures and a changeover to a nonactivated tunneling process at temperatures of the order of 1/2 the optical phonon frequency.

(c) the magnitude of the steady state photoconductivity at low temperatures decreases by approximately a factor of five as the maximum amount of H is added to the unhydrogenated film, while the lifetime barely changes; thus it is inferred that the mobility decreases by a factor of five with H addition. These facts must be considered along with the decrease of the dark conductivity at low temperatures by more than five orders of magnitude with the same H addition. The most likely explanation of the latter is the removal of pseudogap states by compensation of dangling bonds with H. However, this might be expected to increase the lifetime by orders of magnitude, if these same states act as recombination centers. Clearly a more sophisticated explanation of the trivially small alteration in lifetime is required. This is currently under investigation.

II.17 EPR and Photo-EPR in Doped and Undoped Amorphous Ge and Si.

J. R. Pawlik, G. A. N. Connell and W. Paul, Contracts N00014-75-C-0468, NSF DMR75-18477, NSF DMR76-15325, NSF DMR72-03020 and NSF DMR76-01111; Research Unit 6.

The doping of a-Ge with B or P shifts the Fermi level E_f toward a band edge. As a result, changes are observed in the EPR spectra which are caused by the charge in the group of singly-occupied states between E_f and E_f minus an average correlation energy. Thus, for example, our most heavily doped film shows a g-value shifted to 2.0114 (from 2.0190 ± 0.0004 for undoped but hydrogenated), half the spin density, twice the microwave saturation power, narrower linewidth in the T-independent regime and an earlier onset (in T) of the T-dependent regime.

Increases of a few percent in the EPR signal have been observed for undoped hydrogenated Si prepared at $T_s = 25^{\circ}C$ and illuminated with photon energies between 0.8 and 1.8 eV. While $T_s = 25^{\circ}C$ films exhibit only small g-value shifts from the dark signal, the photo-EPR for T_s - $250^{\circ}C$ films has two distinct features suggesting transfer of spins from g-values above the central value for the dark resonance to g-values below it.

III. DECISION AND CONTROL THEORY AND SYSTEM ANALYSIS

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Prof. P. Caines (from 9/1/76)
Prof. Y. C. Ho
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A. SYSTEM ANALYSIS AND CONTROL

III. 1 Nonlinear Oscillatory Devices. R. E. Kronauer and S. Mochon, Contract N00014-75-C-0648, Research Unit 10.

We have been proceeding with the study of a system of coupled self-excited oscillators which has multiple asymptotic states, each state with

a different frequency. The objective is to define limits for switching the system between states by external sinusoidal forcing applied at one access point on the system. We are determining, (1) lower bounds for the forcing strength as a function of external frequency and, (2) which state the system will in fact seek when the forcing is turned off. If the system will go to that free oscillation which is closest in frequency to the preceding forcing, a useful electronic device can be constructed. We have previously shown that for certain forcing frequencies, the system will not proceed to the state with closest free frequency if the forcing is too large. We must therefore determine upper as well as lower limits to the forcing strength. Because of the many relevant parameters of even simple systems, the number of computer runs requires is large.

In studying the lower limit of forcing, we have observed that forcing below the strength necessary to cause the system to synchronize ordinarily leads to a limit cycle in state space as the phase of the forcing advances steadily with respect to one or more of the individual oscillator phases. However, at critical strengths of the forcing the system displays a limit set which is not simple, and has the characteristic of a strange attractor. While this is not of significance for the application which motivates the study since higher levels of force are required for true entrainment, it is of considerable mathematical interest.[1]

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B. CONTROL AND OPTIMIZATION

III. 2 Private and Common Information. Y. C. Ho and Clyde Martin, Contract N00014-75-C-0648 and NSF Grant GK31511; Research Unit 8.

The colloquial concepts of "What you and I both know", the common information, and "What I know that you don't know", the private information, are very intuitive notions which seem to be basic in any theory of large scale information systems. The practical implication of these notions are also obvious in management information system design (MIS), command, control and communication networks (C3), and data base systems. Surprisingly, no previous work has been done towards the precise characterization of these intuitive notions. We have just completed a preliminary study which defines in a precise way these ideas of common and private information in a decision-theoretic framework and demonstrates various reasonable properties which they possess.

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III. 3 Decentralized Control in Data Communications. Frits C. Schoute, Contract N00014-75-C-0648 and NSF Grant GK31511; Research Unit 8.

1. Satellite Communication

Access control to a packet switched satellite channel is an interesting problem that fits in the framework of non-classical control theory, because the stations that communicate through the channel can only share information with considerable delay (round trip time to the satellite) and make decisions in a decentralized way. A simple model is developed for which it can be shown that beyond a certain relative value of the delay the optimal decision rule will be an open loop decision rule. This decision rule is determined for both the case that the packets to be transmitted are 'new' packets and the case that, because of earlier interference of two or more stations, packets need to be retransmitted. Both decision rules are 'simple' from the viewpoint of practical implementation.

2. Symmetric Team Problems and Multi-Access Wire Communication

There are many analogies between packet switched wire communication and packet switched satellite communication. But with regard to communication delay and the typical cost of a communication station there is a great difference: both quantities are much lower in the case of wire communication. Consequently different solution concepts come into use. The new concepts of symmetric team problems (many identical

decision makers with one common objective) and symmetric solutions (the decision makers are restricted to have identical decision rules) are developed and it is shown that the restriction of a symmetric solution may induce randomized decision rules. These concepts are applied to the problem of determining in a decentralized way 'which station will be next in putting a packet on the wire'. It is shown that the cost of the symmetric solution converges to the cost of the unrestricted solution as the number of stations becomes large (given relative low cost of the stations, this is an important consideration). Numerical results are obtained that indicate how fast this convergence is.

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III. 4 Information and Signaling in Many-Person Decision Problems.

Y. C. Ho and M. P. Kastner, Contract N00014-75-C-0648 and NSF Grant GK31511; Research Unit 8.

An important new area in decision and control is that of decentralized control, namely, the study of control systems where there is more than one controller (or decision maker) and each controller has different information. We have focused on the role of information in decision making. In particular, we have been working with an economic model of the job market proposed by Michael Spence, an economist at

Harvard.[1,2] The economic community has been extremely excited about this work because it presents a new way to model the transfer of information. This transfer is called "signaling". In the job market, for example, individuals applying for a job signal the employer about their abilities through their educational levels. That is, an employer believes that a higher educational level indicates higher ability, and offers wages accordingly. We have used this model as a vehicle for insights into the nature of signaling as a particular type of information structure, and have discovered new solutions to this problem and the conditions under which these solutions are stable. Another area of investigation is the study of threshold effects, that is, whether the signaling properties change if the parameters in the problem cross a threshold level. For the Spence model, if the system becomes too noisy or if signaling costs become too high, than signaling will cease.

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3. M. P. Kastner, "Mixed vs. Pure Strategies in Many-Person Decision Problems," submitted to IEEE Transactions on Automatic Control.

III. 5 Scheduling a Large Scale Transportation System. David M. Stein, Contract N00014-75-C-0648 and NSF Grant GK31511; Research Unit 8.

There has been some recent interest in the "Dial-a-ride" proposal for alternative public transportation systems. These schemes ideally provide large numbers of passengers with personalized service. A passenger is taken from his origin to his destination by a small bus; the bus may deviate en-route to collect and deliver additional passengers. In such systems, the central mathematical problem is one of scheduling: the assignment of a passenger to a bus and a time for the trip.

Our research is an analytic investigation into the basic aspects of dial-a-ride scheduling algorithms. Loosely it is based on the following principle. Even though each passenger is unique with his own required origin, destination and time of delivery, in a large system when there is a large number of passengers, the behaviors patterns of the set of all the passengers can be predicted quite closely. This is the "equalizing" effect of the law of large number that has been observed in many physical phenomena, the classic example being the thermodynamic principles for the behavior of gases.

With this approach one is able to design simple dial-a-ride algorithms for which optimality can be precisely measured in a certain asymptotic probabilistic sense; that is, the algorithms perform well with high probability when there is a large number of passengers. A methodology is being developed which allows one to evaluate analytically simple models of proposed schemes and to obtain qualitative insights. For

example, it is easy to investigate changes in performance when parameters (such as the number of buses, the size of the region and others) are varied.

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III. 6 Catastrophe Theory and Its Applications. R. K. Mehra, Contract N00014-75-C-0648; Research Unit 9.

The previous work on the application of Catastrophe Theory to Ignition and Chemical Kinetics was continued. A survey of the literature in the application of Bifurcation Theory to Chemical Kinetics and to Buckling of Structures was performed. This lead to a study of the Hopf Bifurcation for the case of complex eigenvalues crossing the imaginary axis with nonzero velocity. An invited talk on the application of Catastrophe Theory to Fire Modeling was presented at the National Bureau of Standards, Gathersburg, Maryland.

Further application of Catastrophe Theory to Aircraft Dynamics at high angles-of-attack and to transient stability of power systems were also investigated.

III. 7 Multiple Time Series Forecasting Using State Vector Models. R. K. Mehra, Contract N00014-75-C-0648; Research Unit 9.

A computer program was developed and tested on a time-sharing computer service for forecasting of multiple time series. The program tests the data for stationarity, performs automatic differencing and deseasonalizing and constructs both the multivariate autoregressive and state vector models for the stationary time series. The applications considered are interest rate forecasting and hydrological forecasting.

Publications

1. R. K. Mehra, "On the Ignition of Paper and Catastrophe Theory," 1976 Joint Automatic Control, Purdue University, Lafayette, Ind., June 1976.

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III.8 Asymptotic Normality of Prediction Error Estimators. P. E. Caines, Contract N00014-75-C-0648; Research Unit 9.

This work by Caines and Ljung[1] has established the asymptotic normality of a large class of prediction error parameter estimators.[2-4] The observed processes are assumed to be stationary and ergodic and the parameterized process models are taken to be nonlinear regression models. In the Gaussian case the results constitute generalizations of previous results concerning the asymptotic normality of maximum likelihood estimators for (i) processes of independent random variables and (ii) Markov processes;[5] in the general case these results generalize previous results on the asymptotic normality of least squares estimators for autoregressive moving average processes.[6-8] Our asymptotic normality theorem gives formulae for the covariances of the asymptotic (normal) distributions for the parameter estimation errors arising from the specified class of prediction error identification methods. Employing these formulae it is demonstrated that the prediction error method which uses the determinant of the residual error covariance

matrix as loss function is asymptotically efficient with respect to a large specified class of prediction error estimators; this is true for all distributions of the observed processes.

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III. 9 The Controlled Complexity Approach to Linear and Nonlinear System Identification. P. E. Caines, Contract N000-75-C-0648; Research Unit 9.

Let (y, u) denote a pair of multivariate strictly stationary ergodic random processes. For a large class of sets of predictors for y, operating on observations of (y, u), it is shown in this work[1] that a large class of prediction error identification methods (see III. above) generate strongly consistent estimates of the predictor parameters.

One feature of the theory presented in Ref. 1 is that it gives an account of the behavior of parameter estimates generated via predictors that may be simpler than the systems generating the observed processes, a common situation in practice. A second feature is that the theory applies when the observations are not generated by a dynamical system. Further the theory does not require the predictors or observed systems to be linear or non-anticipative.

In the prediction error identification method the complexity of the candidate predictors is chosen by the experimenter. As a result, we refer to our viewpoint as the "controlled complexity" approach to system identification. For linear predictors this notion is made precise in terms of the concept of "degree-complexity". In the general case the relationship between the complexity of a set of predictors and that of a set of observed processes is measured in terms of the notion of "predictor set completeness".

Results in Ref. 1 describe the behavior of prediction error estimators in terms of predictor set completeness. For linear systems

and, in particular, for rational spectrum estimation, a detailed analysis is given using the notion of degree complexity. Applications of the main results to nonlinear predictors are presented and results on the asymptotic normality and accuracy of prediction error estimators are given. Finally open problems are listed.

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III. 10 Numerical Methods. P. E. Caines, Contract N00014-75-C-0648; Research Unit 9.

In this work[1] we devise a new variant of the Generalized Least Squares (GLS)[2-4] identification method. The GLS method estimates the parameters of an autoregressive (AR) process $a(z)y = b(z)u + w$ driven by a noise process w with the AR structure $d(z)w = \epsilon$, where ϵ is a white noise process and u is an observed input process. On the other hand, the method we propose identifies an autoregressive moving average (ARMA) process model, i.e., a model of the form $a(z)y = b(z)u + c(z)\epsilon$. An advantage of using ARMA models is that the zeros of the spectrum of the observed process can be represented with lower order systems than would be required by AR models.

We call our technique the Cholseky Least Squares (CLS) method because the moving average (MA) part of the output process model is estimated using a Cholesky factorization of the residual covariance matrix. There has recently been active research on the topic of computationally efficient or 'fast' Cholesky factorization methods, see e.g., Rissanen[5] and Morf[6]. Our algorithm exploits this work in that it repeatedly calls upon a Cholesky factorization routine. In our computational experiments the CLS algorithm uses the Cholesky factorization algorithm presented by Morf in Ref. 6. These experiments compare the CLS and GLS methods, demonstrating the greater efficiency of the former; they also demonstrate the successful combination of the CLS algorithm with Akaike's Final Prediction Error criterion[7] to produce a fully automatic system order estimation procedure. Finally we show that the CLS algorithm produces estimates of the observed system's underlying impulse response rather than its ARMA description. We believe this to be a property of most successful system identification techniques and is to be expected from the prediction error theory of system identification (see III. and III. above). However, it should be noted that the CLS method does not completely fall into the framework of the prediction error theory.

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III. 11 System Identification. R. W. Brockett and P. S. Krishnaprasad, Contract N00014-75-C-0648; Research Unit 7.

In this work we discuss systematically two possible schemes for scaling single-input/single-output transfer functions and study their implication for system identification. In particular, we identify two different 4-parameter scaling groups which play natural roles in studying linear systems and determine what the effect of scaling is on the Fischer Information Matrix and related statistical measures arising in system identification. The scalings we consider include change of time scale, feedback, exponential tapering, magnitude scaling, etc.

The scaling groups are defined in such a way as to preserve the degree of the rational function. Since they act continuously on the space of rational functions (as topologized in Ref. 2), this means they

preserve the Cauchy index (signature of the Hankel Matrix) as well. This means that the scaling process also gives new insight into the parameterization question for rational functions. Finally, we show that the scaling groups considered are natural in that they cannot be enlarged without becoming completely useless.

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III. 12 Nonlinear Realization Theory. P. Crouch, Contract N00014-75-C-0648; Research Unit 7.

In Ref. 1 below some properties of minimal realizations of finite Volterra series are discussed. In particular, the structure of the kernels and the possible Lie algebras of such systems are described. Some results on the state space of such realizations are announced and some consequences pointed out.

The motivation for discussing systems whose input-output maps are finite Volterra series is two-fold. They are a natural generalization of the linear system and the variation of parameters formula. It will be obvious from the results on the Lie algebras of such systems, that many systems will have infinite Volterra series. In modelling these systems,

it is natural to truncate the series and examine realization for the finite Volterra series.

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III. 13 Computational Complexity. R. W. Brockett and J. Ja'Ja', Contract N00014-75-C-0648; Research Unit 7.

In the implementation of many control schemes via digital computer the complexity of the control algorithm is limited by the power of the computing device available. One measure of the complexity of an algorithm is the number of scalar multiplications which must be done to implement it. In recent papers we have investigated this question for certain basic arithmetical problems which arise in a variety of algorithms. These results are surprising in that they indicate that many standard algorithms are quite poor when measured by this criterion.

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III. 14 Stability. R. W. Brockett and K. Chiou, Contract N00014-75-C-0648; Research Unit 7.

The stability of feedback systems as investigated by the circle criterion and other frequency domain methods has been brought to a new level of completion by our paper[1] which describes the extent to which simple feedback loops can be decomposed into simpler systems. We have also investigated in Ref. 2 extensions of the circle criterion based on Liapunov functions which are not necessarily quadratic. These results are interpreted also as partial confirmation of conventional servo-mechanism practice with respect to feedback compensation.

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IV. ELECTROMAGNETIC PHENOMENA

Personnel

Prof. R. W. P. King
Prof. T. T. Wu
Dr. R. W. Burton (summer
Dr. K. -M. Lee (until June 30)
Dr. D. H. Preis
Dr. S. S. Sandler (part-time)
Dr. L. C. Shen (summer)
Mr. D. J. Blejer
Ms. M. E. Burton (summer)
Mr. H. -M. Lee (after October 1)
Mr. Marvin Morris
Ms. M. Owens
Ms. B. Sandler (part-time)
Mr. R. M. Sorbello (until Sept. 15)
Mr. S. K. Wan (after October 1)

Research in the area of electromagnetic radiation is directed toward the solution of practical problems through the complete understanding of the underlying physical phenomena. This involves the coordinated application of modern analytical, numerical and experimental techniques and the use of high-speed computers and precision instrumentation. Most practically significant problems in this area are sufficiently complicated that extensive computation and measurement are often required to justify approximations that are usually necessary. Where possible, general formulas are obtained and verified experimentally so that the phenomenon under study can be understood physically in analytical form and not just as a set of numbers.

The researches are conveniently grouped under two main headings, viz., antennas and waves in and over dielectric, conducting, and plasma media, and antennas in air. The first group is concerned with the circuit, radiating, and scattering properties of antennas and arrays and

the waves generated by them in their dependence on the electrical properties of a material medium (lake or sea water, earth, ice, living tissue, plasma, etc.) in various forms and degrees of proximity. The antennas may be directly embedded in the medium or separated from it by a layer of insulation. The second group of investigations deals with the detailed electrical properties of complicated metal radiating and scattering structures in air including especially electrically thin and thick crossed conductors used to model an aircraft.

A. ANTENNAS AND WAVES IN AND OVER DIELECTRIC, CONDUCTING, AND PLASMA MEDIA

IV. 1 Theoretical and Experimental Investigations of Insulated Linear Antennas in Various Dissipative Media. K. -M. Lee, R. W. P. King and T. T. Wu, Contracts N00014-75-C-0648 and F44620-72-C-0021, Research Unit 11.

The model of a finite, highly-conducting, tubular antenna that is center-driven by an ideal delta-function generator, surrounded by an infinitely long insulating cylinder (with wave number k_2), and immersed in a dissipative medium of infinite extent (wave number k_4) has been studied theoretically.[1] The integral equation for the current is derived and found to be similar in form to that for a bare cylindrical antenna in an infinite dissipative medium, but with a more complicated kernel and an arbitrary constant κ instead of k_2. The properties of the kernel are discussed in detail and approximate solutions for the complex wave number are obtained that are valid for different ratios of the wave numbers, k_4/k_2. These solutions are compared with numerically computed values of the wave number in a table for four values of b/a and six different ambient media; air is the insulating material in all cases. A numerical method for solving the integral equation for the current is discussed and compared graphically with measured data and an approximate iterative method based on an earlier zero-order solution,[2] but with the new, more general expressions for the wave number k_L and the characteristic impedance Z_c. It is shown that the transmission-line-like, zero-order solution applies for $|k_4/k_2| \geq 2$ when the

generalized forms for k_L and Z_c are used. This is considerably less restrictive than the condition, $|k_4^2/k_2^2| \gg 1$, originally assumed in the theory. For $1.0 < |k_4/k_2| < 2.0$, a semi-empirical formula has been obtained[3] in which the weighting factor k_2^2/k_4^2 plays an important role.

A series of experiments paralleling the theoretical treatment have been performed. Measurements of the currents, charges and admittances of air- and melamine-insulated antennas immersed in fresh water and salt water have already been reported.[4-6] These results for $|k_4/k_2| \geq 3.8$ were found to agree well with theory. During this reporting period a paper has been prepared[7] which presents the measured currents and admittances of air- and oil-insulated linear antennas immersed in sand, for which $|k_4/k_2| \geq 1.3$. These data are compared and found to be in good agreement with the zero-order solution when the more general expressions for k_L and Z_c are used. The problems involved in approximating experimentally the ideal theoretical model are discussed as well as various uncertainties in the measurements. The effect of a thin-walled plastic container on the properties of a liquid-insulated antenna were measured and displayed graphically. The results agree with an earlier theoretical determination.[5]

A separate theoretical and experimental study has been made[8] of a center-driven, insulated linear antenna terminated at each end in a bare quarter-wave extension of the antenna and immersed in a relatively dense dissipative medium. The analysis is based on the theories of the bare antenna and the completely insulated antenna in a relatively dense ambient medium. Approximate expressions are derived for the current distribution and admittance and are solved using the generalized forms

for k_L and Z_c. Comparisons are made with measured data taken on air-insulated terminated monopoles in fresh and salt water. Finally, it is pointed out that by adjusting the radius (b/a) of the insulation or the ratio of the wave numbers (k_4^2/k_2^2), it is possible to match the characteristic impedance Z_c of the insulated antenna to the apparent input admittance Z_{sa}^{-1} of the bare, quarter-wave antenna to obtain a nearly pure traveling wave. If necessary, a power-absorbing resistor can be connected in series with the bare section. A graph of the values of Z_c for specific values of b/a and k_4^2/k_2^2 is provided.

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IV. 2 Theoretical and Experimental Study of Coupled Insulated Antennas Immersed in a Relatively Dense Medium. R. W. P. King, T. T. Wu, and L. C. Shen, Contracts N00014-75-C-0648 and F44620-72-C-0021; NSF Grant ENG 74-13705 with the University of Houston; and NSF Grant GK-40575 with Northeastern University, Research Unit 11.

Since the single insulated antenna in a relatively dense medium corresponds in its directive properties to a long collinear array of bare elements, it should be a very useful element in highly directive broadside and endfire arrays designed either for direct transmission through the medium or for lateral-wave transmission along the interface between a semi-infinite medium and air. Owing to the high exponential attenuation in sea water, parallel insulated antennas interact significantly only when very closely spaced. On the other hand, when in lake water, the same antennas should experience strong interactions over quite large distances. This is a consequence not only of the low attenuation in the fresh water, but also of the electrically long lengths of the antennas. These may be many wavelengths long in the ambient medium and yet contain only substantially unidirectional currents along each insulated element. Evidently, the interaction of coupled insulated antennas is very different from that of the same antennas when bare. In order to provide a physical basis for understanding the phenomena involved and make available a

quantitative background, a complete theoretical and experimental investigation was made.

The distributions of current and driving-point admittances for the parallel, identical elements of a circular array have been determined theoretically[1] when these are individually insulated and immersed in a general ambient medium that is assumed to be homogeneous, isotropic, and relatively dense compared with the insulating material. The distances between the elements are sufficiently great so that approximate rotational symmetry obtains locally for each antenna with its insulating sleeve. The formulation is for an n-element circular array with n phase sequences; special attention is given two- and three-element arrays. The approximations are the same as those for the single insulated antenna;[2] the results are again of zero-order. The distributions of current are transmission-line-like for each phase sequence, but with different complex wave numbers that depend not only on the electrical properties of the insulating and ambient media but also on the coupling among the elements. Numerical results are presented for the wave numbers, input admittances and current distributions of a two-element array for each phase sequence with parameters that correspond to an insulating cylinder of air and an ambient medium of lake water.

Extensive measurements have been made of the properties of coupled conducting monopoles with air insulation in thin acrylic tubes immersed in a fresh-water lake.[3,4] All data were obtained with the antennas driven both in phase and in phase opposition. Current distributions and input admittances have been measured for three thicknesses of the insulation ($c/a = 2.5$, 4.0 and 8.0), four antennas

lengths (h = 15, 30, 45 and 60 cm) and a wide range of separations (d = 7.64 to 38.1 cm in steps of 3.82 cm). Note that the value of k_L varies with the size of the insulation so that the electrical lengths $\beta_L h$ of the antennas also differ for different values of c/a. A comparison is made in the second paper[4] between the measured data and theory, and generally good agreement is observed for the currents. Differences in the admittances due to the effects at the junction between the monopole and the driving coaxial line and the approximations of the theory are discussed. Since the choice of a dielectric ambient medium with a large permittivity is a more sensitive test of the theory than either a more conducting medium or a medium with smaller permittivity, it seems reasonable to assume that the simple formulas developed for the phase-sequence currents and admittances should be at least as accurate for antennas in other media that satisfy the condition $|k_4^2/k_2^2| >> 1$ as they are for antennas in lake water.

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IV. 3 Theoretical and Experimental Study of the Beverage-Wave Antenna.

R. M. Sorbello, K. -M. Lee, L. C. Shen, R. W. P. King, S. S. Sandler, and T. T. Wu, Contracts N00014-75-C-0648 and F19628-75-C-0057, Research Unit 11.

The results of a theoretical and experimental study of the circuit properties (current, charge and admittance) of single-wire antennas placed horizontally above an imperfectly conducting half-space have been reported.[1] The antennas are either open-ended or terminated in a resistor connected to a quarter-wave section of line to form the modified Beverage antenna with its characteristic traveling-wave distribution of current. Unlike earlier work, this study has investigated the effect of the half-space on the properties of the antenna. The theory of King, Wu and Shen[2] for the unloaded horizontal-wire antenna above a dissipative half-space is extended to apply to terminated antennas and, specifically, to symmetrically and asymmetrically driven, modified Beverage antennas. Measurements made on both types of horizontal antenna, of three different lengths, when placed at varying heights ($d/\lambda_0 = 0.01$ to 0.25) above fresh water, salt water and moist earth are described and compared with the corresponding theory. The results indicate the need to include end effects in the theory. The physical reason for this is that the original assumption that radiation into the air is negligible compared to the power transfer into the imperfectly conducting or dielectric half-space is a good approximation only when the antenna is quite close to the earth ($d/\lambda_0 \leq 0.02$). In order to generalize the theory to greater antenna heights, account must be taken of radiation into the air. It is shown[3] that the transmission-line form for the current remains a

reasonable approximation for heights up to at least $d/\lambda_0 = 0.25$ and that the effect of radiation into the air can be treated approximately as a property of the open end in the shape of a lumped terminating impedance. In this paper the generalization is verified by a comparison of theory and experiment for short-circuited (effectively infinite), open-ended (finite), and terminated (Beverage) antennas over fresh and salt water.

A parallel study of the radiating properties of the Beverage-wave antenna has been completed.[4] Useful approximate forms developed earlier by Norton have been used in this study, the only difference being that in the present analysis the exact expressions for the antenna current are used rather than an assumed current distribution. An expression for the space-wave radiation pattern is formulated using a "geometric optics" approximation, while the superposition principle is used to sum the fields of individual infinitesimal dipoles to obtain the surface-wave radiation pattern. Expressions for a number of useful antenna parameters (efficiency, front-to-back ratio, antenna gain, effective length) are then derived. Measurements of the surface-wave radiation patterns of Beverage antennas placed over fresh water and dry earth were made to determine the effects of antenna spacing and the properties of the half-space. The measurements also served to verify that asymmetrically driven, modified Beverage antennas can be used to obtain unidirectional surface-wave and space-wave radiation patterns equivalent to the radiation patterns of the conventional Beverage antenna. The conclusion is reached that modified Beverage antennas should be excellent elements in highly directive broadside arrays.

The development by Dr. S.S. Sandler of an alternative approach to compute numerically the currents and fields of antennas located above or in a complex or simple medium through an iterative procedure is in progress.

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IV.4 Theoretical and Experimental Study of Coupled Horizontal-Wire Antennas Over a Conducting or Dielectric Half-Space. L.C. Shen, K.-M. Lee, and R.W.P. King, Contracts N00014-75-C-0648 and F19628-75-C-0057, Research Unit 11.

The circuit properties of coupled parallel horizontal-wire antennas above an electrically dense dissipative half-space have been studied theoretically and experimentally.[1,2] The complex wave number,

distribution of current and admittance of the antennas are determined theoretically for symmetrical and antisymmetrical excitations. The theory is approximate in the same sense as the earlier theory for the single horizontal-wire antenna in that radiation into the air is neglected and a limitation to small heights is imposed. It is generalized, as for the single horizontal antenna, to take account of radiation into the air through a complex terminal function and so enlarge its range of validity while preserving the transmission-line form for the current. The numerical values of the terminal function are determined from a least-squares fit of the measured and theoretical current distributions. Current measurements were made on coupled horizontal antennas, driven in zero-phase and first-phase sequences, for six different antenna separations and three different heights above fresh- and salt-water solutions. The antennas were either open-ended or terminated in a lumped resistor and a quarter-wave extension of the antenna to produce traveling-wave distributions of current. Good agreement is displayed between theoretical and measured currents on the open-ended antennas and between theoretical and measured values of the terminal function for the terminated, modified Beverage antennas.

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IV. 5 Theoretical Study of the Scattering from an Obstacle Above the Earth. H. -M. Lee, Contract N00014-75-C-0648, Research Unit 11.

The properties of radiating and scattering structures in the presence of a dissipative or dielectric half-space like the earth are complicated since they involve not only the shape, dimensions, and height of the obstacle but also the electrical properties of the earth. Preliminary work has begun on a theoretical investigation to determine: a) the induced currents and scattered field of the obstacle when isolated; b) the scattered field from the surface of the earth in its relation to its reflecting and absorbing properties; and c) the interaction between the currents in the obstacle and those in the earth, and the resulting modification of the reflected field from the obstacle. The obstacle is being modelled by a thin-wire loop and by combinations of loops to form three-dimensional structures. These configurations will be studied when illuminated by an incident electromagnetic wave arriving at an arbitrary angle and with arbitrary polarization.

IV. 6 Experimental Study of the Insulated Traveling-Wave Antenna Submerged in a Poorly Conducting Medium. L. C. Shen, R. W. P. King and R. M. Sorbello, Contracts F44620-72-C-0021, N00014-75-C-0648 and F19628-75-C-0057, and NSF Grant ENG 74-13705 with the University of Houston, Research Unit 11.

There are various occasions when it is necessary or advantageous to have complete antenna system beneath the surface of the earth or a

lake. Since the attenuation of a direct or lateral wave from a submerged source is often very great, highly directive subsurface antennas may be essential if communication over even moderate distances is to be achieved. Although most of the theoretical analyses of antenna radiation in the presence of a two-medium boundary in principle apply to materials with arbitrary dielectric and conducting properties, useful formulas usually require one of the media to be highly conducting, that is, $\sigma >> \omega\epsilon$, so that the displacement current in the medium is entirely negligible. Thus, formulas provided by most of the available theoretical treatments are not applicable to the case, for example, of a directional traveling-wave antenna submerged in a lake for which $\sigma/\omega\epsilon = 0.094$. Only integral expressions of the fields of an infinitesimal dipole are available. The extension of a numerical technique for the evaluation of the integrals to media other than sea water is discussed under the following topic. It also appears that no experimental information is available on an electrically long, traveling-wave antenna submerged in a poorly conducting medium and operated at a frequency such that $\sigma << \omega\epsilon$.

An experimental study to measure the field of a directional traveling-wave antenna submerged in a lake has been completed.[1] The field patterns with the receiver both under and over the surface of the water are seen to be quite directional. The measured relative strength of the electric field as a function of the radial distance from the source is also shown. The rate of decrease with distance of the radial component of the field in the water agrees with theoretical predictions.

Reference

1. L. C. Shen, R. W. P. King, and R. M. Sorbello, "Measured field of a directional antenna submerged in a lake," IEEE Trans. Antennas Propagat., Vol. AP-24, 891-894, November 1976.

IV. 7 Numerical and Analytical Determination of Electromagnetic Fields of Antennas in the Earth Near Its Interface with Air. B. H. Sandler, Contracts N00014-75-C-0648 and F44620-72-C-0021, Research Unit 11.

The numerical study by Siegel and King[1] for antennas in a conducting medium near an interface with air has been extended to other than conducting half-spaces.[2] The three cylindrical components of the electric field of a horizontal electric dipole in sea water, lake water and dry earth have been computed and intercompared as functions of the frequency and of the distance between the source and the receiver. It is concluded that E_ρ is the only generally useful component. It alone is either greater than or at worst only slightly smaller than both of the other components over the wide range of distances, frequencies and properties of the media so far investigated. Transmitting and receiving antennas must be designed with this in mind because of the quite different characteristics required to respond to E_ρ instead of the conventional E_ϕ used in unbounded media. The applicability of the approximate analytical formulas of Banos is examined. It is seen that over restricted ranges Banos' approximate formulas are in good agreement with the numerically determined results. This is significant, on the one hand,

as a check on the numerical evaluation and, on the other hand, as a means of making the simple analytical formulas available over extended and known ranges. Finally, the numerical results are confirmed experimentally through comparison with selected data measured by Siegel and King[3] and by Shen, King and Sorbello.[4]

Current work on this problem is being devoted to developing a uniform procedure for handling the integrals over all ranges of the parameters.

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IV. 8 Experimental Study of the Electromagnetic Field of Bare and Insulated Antennas in Material Media. G.S. Smith, Contract F44620-72-C-0021, Research Unit 11.

Field patterns of bare and insulated circular-loop antennas immersed in fresh water have been measured and the results reported.[1]

Comparisons are made between bare and insulated loops of the same size and between insulated loops with spherical and toroidal insulations for two different loop sizes. It is seen that the effect of the dielectric insulation in altering the field pattern of a loop antenna in a material medium is especially noticeable when the bare loop is electrically large in the material medium and the medium has low dissipation. The results also indicate that similar field patterns can be obtained with insulations of different shape.

A similar set of measurements has been made on bare and insulated linear antennas immersed in fresh water.[2] In this case, limitations due to the physical dimensions of the experimental model made it impossible to measure the far-zone field directly so that an alternative approach was required. The electric field tangential to a spherical surface at a distance $R = 10\lambda$ from the antenna was measured in amplitude and phase and then transformed to obtain the far-field pattern. Measurements were made on linear antennas ranging in length from $0.5\,\lambda \leq h \leq 3.0\,\lambda$. The field patterns of bare antennas and of insulated antennas with concentric and eccentric insulation are compared. The effect of varying the diameter of the insulating Teflon cylinder was also investigated. The measured field patterns are in good agreement with theoretical patterns calculated from recently developed theories applicable to concentric and eccentric insulations.[3,4]

References

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4. T.T. Wu, L.C. Shen, and R.W.P. King, "The dipole antenna with eccentric coating in a relatively dense medium," IEEE Trans. Antennas Propagat., vol. AP-23, 57-62, January 1975.

IV.9 Transmission and Reception with Bare and Insulated Antennas Embedded in Skin. R.W.P. King, Contract N00014-75-C-0648, NSF Grant GK-40575 with Northeastern University, and Los Alamos Scientific Laboratory, Research Unit 11.

For various telemetric applications such as, for example, the electronic identification of animals, encapsulated transponders are embedded in or just below the hide. These include an antenna that is illuminated by a beam from an outside interrogator. The successful operation of such a device both in reception and transmission depends critically on the properties of the antenna when embedded in the dissipative medium. The design of practical receiving and transmitting antennas for embedding in a dissipative medium near its boundary with the surrounding air has been investigated. First the receiving qualities of antennas when embedded a short distance below the surface of a dissipative material with the properties of skin were analyzed[1] in terms of the complex transfer function and the properties of the antenna. (Since the electrical properties of muscle are quantitatively quite similar

to those of skin, the results are also meaningful for it.) The types of antenna investigated include bare and insulated dipoles as single elements and in two-element broadside arrays. The eccentrically insulated dipole is also studied. Actual voltages across practical load impedances are determined when the antennas are embedded specifically at depths of 0.1, 0.5 and 1.0 cm in hide or skin. The results indicate that with the proper choice of antennas, frequency and load, significant voltages can be maintained when the incident field does not exceed the prescribed maximum. It is shown that the frequency for maximum voltage across the load with skin as the material is 700 MHz and that resonant bare dipoles have a practical length. However, the higher directivity of insulated dipoles provides comparable voltages with the same antennas and loads at 3 GHz. Application of the formulas and procedures to other media than skin is straightforward. A similar but more involved analysis is required if quantitative account is to be taken of a subcutaneous layer of fat between the skin and muscle.

With the application of the reciprocal theorem, the transmitting qualities of antennas embedded in a dissipative half-space with the characteristics of skin are then obtained from the previously determined receiving properties.[2] A quantitative study is made of transmission and reception between a 10-element Yagi array in air and two-element arrays of bare and insulated dipoles embedded in a dissipative half-space. The distance between the embedded transmitter and outside receiver is 4.28 meters at the optimum frequency of 700 MHz or 1 meter at 3 GHz. If the outer unit must be placed at greater distances from the surface of the skin, more directive antennas than the 10-element Yagi array can be provided, though these are likely to lack the structural simplicity of the Yagi.

IV. 10 The Finite Cylindrical Antenna in a Warm Isotropic Plasma.

M. A. V. Ward, NSF Grant ENG 75-14455 and Contract N00014-75-C-0648; Research Unit 11.

This research project has been completed. The first of two publications issuing from this investigation has been prepared.[1] In it are considered both the formulation and the solution of the Maxwell-Vlasov equations for a hot, isotropic, homogeneous plasma which occupies the region exterior to an infinitely long, perfectly conducting rigid cylinder. The problem is formulated rigorously. The assumption of circular symmetry and specular reflection of electrons at the antenna surface yields coupled integral equations in radial and axial electric-field components. The kernels of these equations are complicated six-fold integrals. The boundary relationship between the perturbed electron distribution function and the electric field at the antenna surface can be simplified under certain conditions. Subject to these conditions, the equations are then solved for Fourier-transformed antenna current and charge distributions maintained by a delta-function generator at the center of the antenna.

Reference

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IV.11 Experimental Studies of Antennas in Plasmas. D. H. Preis, NSF Grant ENG 75-14455 and Contract N00014-75-C-0648; Research Unit 11.

Experimental results have been reported[1] for antennas operated in the 500-1000 MHz frequency range in helium d.c. discharge tubes. The measurements included both the radial electric field and the azimuthal magnetic field near the (cylindrical) antenna surface and along its length. The antenna charge distribution derived from the measured current distribution using the continuity equation for a dissipative medium did not totally agree with the measured charge distribution. This indicates, perhaps, that the cold-plasma model does not account for all the currents (electron fluxes) across the boundary between the antenna and the plasma.

Experimental work has continued in this area. Specifically, a more accurate probing system has been developed which can be calibrated precisely. Data from the probes are taken rapidly by a computerized data-acquisition and data-analysis system which plots actual antenna current and charge distributions on an X-Y plotter during the course of experimentation. The present experimental system employs a larger volume of plasma than the previous system. It is expected that this experimental arrangement will yield considerably more accurate results.

Reference

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B. ANTENNAS IN AIR

IV. 12 Investigations of Electrically Thin Crossed-Dipole Antennas.

R. W. P. King and T. T. Wu, Contract N00014-75-C-0648; Research Unit 11.

A subject of considerable interest and importance with reference to the shielding properties of aircraft when exposed to an electromagnetic pulse (EMP) is the determination of the currents and charges induced on the metal surfaces. The electrically thin crossed-dipole receiving and scattering antenna is an appropriate model to consider in order to gain insight into the problem. A complete theoretical and experimental study of the currents and charges induced on single and crossed electrically thin monopoles by a normally incident plane electromagnetic wave has been reported earlier.[1-3]

The nature of the required boundary conditions when electrically thin conductors of different cross-sectional size meet has been determined from an analysis of the tapered antenna.[4] It is shown that the correct average boundary condition at the junction is not the continuity of surface density of charge as has been assumed in the past, but rather that the product of the charge per unit length, q, and the expansion parameter Ψ is the quantity that is constant in a change of radius. When the conductors are all electrically very thin, all of the Ψ_i's may be so large that the following approximate relation obtains: $q_1 \doteq q_2 \doteq \ldots \doteq q_i \doteq \ldots \doteq q_n$.

The currents in a thin-wire cross with mutually perpendicular arms of equal length and radius have been determined when the incident field is not normally incident and the electric vector is not required to be parallel to one of the members.[5] The analysis is formulated in general terms but explicit formulas are obtained only for the zero-order currents

which are generally adequate to determine the scattered field of very thin wires. The relatively simple formulas consist of even and odd parts for both the vertical and horizontal wires; they include components due to mutual coupling as well as those excited directly by the incident field. The method for obtaining the much more complicated first-order currents needed for near fields is indicated.

A summary has been written[6] which reviews the coordinated application of theory and experiment to determine the induced currents and charges on circular, highly conducting cylinders in a normally incident plane-wave field in the following sequence: 1) infinitely long cylinders with unrestricted radii; 2) electrically thin cylinders of finite length; 3) electrically thin crossed cylinders; 4) tubular cylinders with unrestricted radii and finite length; and 5) crossed electrically thick cylinders.

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IV.13 Numerical and Experimental Study of the End Effect for a Monopole Driven from a Coaxial Line. Marvin Morris, supported by Sandia Laboratories, Albuquerque, N.M.

This research project is essentially completed. An experimental study requiring very high precision was conducted on the junction effects of antenna driven by coaxial lines. Admittances were measured as a function of b/a, the ratio of outer coaxial conductor diameter to antenna diameter, and the length of the antenna. Dielectric plugs of different dielectric constants and of different lengths were placed in the end of the coaxial line and the measurements were repeated. The coaxially driven infinite monopole antenna immersed in a dissipative medium and with a dielectric plug in the end of the coaxial line, as well as the coaxially driven finite tubular monopole have been formulated as coupled pairs of singular integral equations and numerically evaluated. The case $a/b \to 0$ for the coaxially driven infinite monopole has been examined. Final theoretical refinements are now being made.

IV. 14 Numerical Methods for EM Problems. D. H. Preis, Contract N00014-75-C-0648; Research Unit 11.

Several different methods have been developed and used to evaluate potential integrals which occur in the numerical solution of electromagnetic scattering or radiation from electrically thin elements.[1] Exact and approximate representations are obtained for potential integrals with constant, trigonometric, or polynomial distribution functions. Each integrand and integral is displayed graphically over a broad range of parameters. The computational efficiency and accuracy range of these representations are given and compared with direct numerical integrations using the Romberg tableau and Gaussian quadrature. Relative computational times varied over a range of about 500 to 1 (using a Hewlett-Packard 9821 digital computer). The representations significantly improve computational efficiency in many cases. Gaussian quadrature was faster than the Romberg tableau by a factor of at least 2 up to at most 15 for the numerical integrations. The results of the research should be useful in the computer solution of integral equations (as well as computer moment-method formulations) for practical electromagnetic problems which involve linear radiators, antenna arrays or wire scatterers.

Reference

1. D. H. Preis, "A comparison of methods to evaluate potential integrals," IEEE Trans. Antennas Propagat., vol. AP-24, 223-229, March 1976.

IV. 15 Development of Computerized Instrumentation to Record and Reduce Measured Data. D. H. Preis, Contract N00014-75-C-0648; Research Unit 11.

A versatile, computerized data-acquisition and data-processing system has been developed. The system is flexible and can be used in a wide variety of electromagnetic experiments. Analog signals (such as voltages from small probes which are sensitive to electric or magnetic fields) are sampled on computer command. Each analog signal is converted into a three-and-one-half digit, parallel output, binary code using a digital multimeter. This parallel output is then converted to a serial binary output through a parallel-to-serial converter. Data in this form are accepted by the computer and stored in its memory. At the user's option, the data may be reduced, printed on paper tape, plotted on an X-Y plotter, or recorded on magnetic tape. The maximum data rate is three samples per second and can otherwise be controlled by the calling computer program. A special interface has been constructed which selects any of three separate data channels (e.g., magnitude and phase of probe voltage and probe position). With each data sample this interface provides a binary code indicating which of the three incoming data channels is "on line." The computer may be programmed to request a specific data channel with its audible, internal tone generator. With the system it is possible, for example, to acquire and plot over one hundred data points for the current and charge distributions along an antenna or scatterer in less than five minutes. Applications of this data-acquisition and data-processing system include:

1) experiments having slowly varying or drifting electromagnetic parameters which would normally introduce (hysteresis) errors in the measurements; 2) experiments for which extensive amounts of data are required; and 3) real-time experimental analysis, adjustment and optimization.

IV. 16 Currents and Charges Induced on the Surfaces of Electrically Thick Cylinders and Crossed Cylinders by an Incident Plane-Wave Field. R. W. P. King, D. J. Blejer, S.-K. Wan, R. W. Burton, L. C. Shen, B. H. Sandler, M. E. Burton, and T. T. Wu, Contracts F29601-75-C-0119 and N00014-75-C-0648; Research Unit 11.

The problem of determining the currents and charges induced on the metal surfaces of a rocket or aircraft that is exposed to an intense electromagnetic pulse when the structure is modeled by a thin-wire cross has been discussed under topic #12. A related investigation of the currents and charges on the surfaces of electrically thick crossed cylinders--a more realistic model--is being conducted.

A theoretical and experimental study has been completed of the surface currents and charges induced on an electrically thick (ka = 1) conducting tube illuminated by a normally incident plane-wave field.[1,2] This is a necessary first step in an investigation of crossed thick cylinders because the effects of adding an intersecting horizontal arm depend on the current and charge conditions on the vertical cylinder at the junction.

Also, since there is no theory for crossed thick cylinders, it was important to develop and verify as accurate experimental apparatus and techniques for the single cylinder that can then be used with confidence in measuring the currents and charges on the cross. The amplitude and phase of the outside surface densities of charge and of axial and transverse current have been measured for cylinders of electrical half-length $kh = 1.5\pi$ and 3.5π. These data were used to plot contour diagrams of the charge density, vector diagrams of the real and imaginary parts of the outside surface current density, and current polarization ellipses. Results for cylinders with open, flat or hemispherical ends have been compared. On the theoretical side, numerical results have been computed using C. C. Kao's program for finite, electrically thick, infinitely thin-walled cylinders in an E- or H-polarized field. An analytical representation was developed in terms of forced and resonant transverse Fourier components. This formulation was then modified to permit the definition of distinct theoretical "inside" and "outside" currents and charges for direct comparison with the measured "outside" values. Theoretical computations were extended to cylinders of electrical half-length $0.5\pi \leq kh \leq 3\pi$ in order to determine the nature of the axial periodicity in the distributions of current and charge.

Horizontal arms of half-length $k\ell = \pi$, 1.5π, and 2π were then joined successively to the vertical cylinder ($kh = 3.5\pi$) at two different junction locations, viz., $kh_1 = 2\pi$ and 2.5π (conditions, respectively, of charge minimum/current maximum and charge maximum/current minimum). The electrical thickness remained $ka = 1$. Extensive measurements were made of the distributions of surface current and charge on the vertical and horizontal members of the various crosses,

and the results were compared with the corresponding theoretical distributions on isolated cylinders of the same length in either an E-polarized field (vertical cylinder) or an H-polarized field (horizontal cylinder).[3] Full-scale relief maps of the surface density of charge on an isolated cylinder ($kh = 3.5\pi$) and a cross with $kh_1 = 2.5\pi$, $kh_2 = \pi$, $k\ell = 2\pi$ have been constructed as an interesting means of visualizing the charge distributions and the effect of the junction. Finally, a detailed comparison has been made of the effects on the distributions of current and charge density on the crossed cylinders by each of the following variables: 1) The electrical length $k\ell$ of each horizontal arm for each fixed location of the junction along the vertical member. Experimental data for $k\ell = \pi$, 1.5π, and 2π have been studied and the differences in the charge and current densities on the vertical cylinder have been described and explained. 2) The location kh_1 of the junction for each length $k\ell$ of the horizontal arms. Measured currents and charges for the locations $kh_1 = 2\pi$ and 2.5π have been analyzed.

A study of the differences between charges induced on the illuminated side of a single vertical cylinder with $ka = 1$ when excited by an ideal plane wave (theoretical data), the approximately plane wave generated by the corner-reflector at a distance of 7.5λ (measured data), and a cylindrical wave generated by a long collinear antenna quite near the cylinder (newly measured data) has been made in order to confirm that certain differences observed between theoretical and measured data were due to the only approximately plane wave front of the field of the corner-reflector antenna. This completes the work on cylinders with $ka = 1$, a full description of which is given in a series of Air Force reports.[4,5]

The next major phase of the investigation, now underway, is a comparable study of currents and charges on cylinders with ka = 2. Certain modifications have been made to Kao's program for cylinders of finite length due to increased storage requirements and theoretical densities of inside and outside surface currents and charges with ka = 2 and kh = 3.5π, 5π and 7π are being studied. Since the theory treats only tubes with open ends, currents and charges are also excited on the inside surfaces. With ka = 1 these are significant only near the open ends; when ka = 2, however, the tubes are above cut-off and permit the propagation of the TE_{11} mode inward from the open ends. As a result, theoretical outside and inside currents are comparable in magnitude with quite different distributions. A first step in the experimental phase has been a study of the effect of using capped ends to avoid the problem of waveguide coupling inside the tubes. The condition ka = 2 is achieved experimentally by doubling the frequency. This involves a different generator and vector voltmeter and new problems relating to the plane-wave nature of the wave front and the noise level. These have been resolved and measurements on cylinders with ka = 2 are in progress.

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IV. 17 Currents and Charges on Cylinders in a Parallel-Plate Transmission Line. R. W. P. King, S.-K. Wan, D. J. Blejer, and T. T. Wu, Grant AFOSR-76-3073 and Contract N00014-75-C-0648; Research Unit 11.

Construction is in progress of a model parallel-plate structure between two tapered sections, one of which extends to a pulser or high-frequency generator, the other to a suitable matching impedance. It has been designed for use at single frequencies or with an electromagnetic pulse such as might actually illuminate an aircraft. Such a pulse consists of an essentially plane, traveling wave front with the mutually perpendicular electric and magnetic vectors transverse to the direction of propagation. It is the purpose of this study to determine how effectively the parallel-plate structure is able to simulate such a plane-wave field by repeating

the surface current and charge measurements on thin and thick cylinders and crossed cylinders (described under topics #12 and #16) but with the superstructure present. A comparison of the two sets of data should provide direct evidence about the efficacy of the model simulator as a generator of traveling plane waves since the corner-reflector antenna used in the earlier measurements has been shown to generate an approximately plane wave from a sufficient distance. Special attention will be directed to the distribution of charge density on the illuminated side of each cylinder since this is particularly sensitive to the nature of the incident wave front. Direct measurements of the electric field along and between the parallel plates by means of small, suitably designed probes are also planned.

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